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Registration of intraoperative 3D ultrasound with preoperative MRI data for navigated surgery – first results at the knee

Claudia Dekomien (1), Stephanie Hold (2), Karin Hensel (2),
Georg Schmitz (2), Susanne Winter (1)

(1) Institut für Neuroinformatik, Ruhr-Universität Bochum, 44801 Bochum, Germany
E-mail: Susanne.Winter@neuroinformatik.rub.de
(2) Lehrstuhl für Medizintechnik, Ruhr-Universität Bochum, 44801 Bochum, Germany

INTRODUCTION

The trend towards minimally invasive surgery leads to an increasing demand for navigation systems. Image based navigation provides the surgeon a three dimensional orientation to control the position of the instruments within preoperative data of the patient.

At the beginning of an image based navigated surgery the coordinate system of the preoperative image data needs to be registered within the coordinate system of the patient. Most of the commercial systems use landmarks as reference for the registration. The registration method developed by our group [1] is based on intraoperative freehand ultrasound imaging and overcomes some problems related to landmark based registration like invasiveness, inaccuracy and the time consumption of the process. Our system showed a high accuracy in phantom data [2] and reliable results in registering 3D ultrasound patient data with CT data of the lumbar spine [3]. Due to a good contrast in imaging of joint surrounding soft tissue and cartilage, MRI scans are of high diagnostic importance and often part of the preoperative routine. Hence navigation that is based on preoperative MRI images instead of CT data, is desirable especially for the knee surgery, where CT imaging plays a minor role.

The main problem with MRI data compared to CT data is the difficulty of bone surface segmentation. Our method bases on a surface-volume registration algorithm which requires the extraction of the bone surface in the preoperative data.

We started with a semi-automatic method, where we extracted that bone surface points from the MRI data that we can depict with a 3D ultrasound scan. In this work we show the first results of the registration of 3D ultrasound and MRI data of the femur and the tibia.

METHODS

3D ultrasound, and 3D T1- and T2-MRI data was acquired from the distal femur and the proximal tibia of a subject. The ultrasound data was pre-processed to enhance the contrast of the bone surface. To emphasize the bone surface in the MRI data, T1- and T2-MR images were combined. Therefore the T1- and a negative of the T2-MR images were added with different weights. Additionally the T2 weighted data was pre-processed with a bias correction algorithm.

For the registration that bone surface points were extracted from the MRI, that could be demonstrated in the ultrasound data. Parts of the bone surface were better to distinguish in T1 and others in T2 MRI. Therefore the bone surface extraction of the femur was achieved in the pre-processed T2 data and the bone surface extraction of the tibia in the T1/T2 combined data.
The registration was performed by a surface-volume registration algorithm which uses an adaptive evolutionary optimization strategy (the CMA-ES) to solve the optimization problem.
For the evaluation we defined a reference registration by a manual pre-registration, followed by multiple local optimizations and a visual control of the result. 100 starting positions were randomly created with a pre-defined maximum translation deviation of 10 mm to the optimum and a rotational deviation up to 11 degree. The registration was considered as correct when the distance of the surface to the optimum was less than 1 mm.

RESULTS

We registered two ultrasound datasets of the femur and one of the tibia, each with and without data pre-processing to enhance the bone surface. Figure 1 shows sagittal and axial slices of the femur and sagittal slices of the tibia. On the left the ultrasound data is depicted, on the right the corresponding, registered MRI is shown and in the middle the overlay of both datasets.
The evaluation of the registration demonstrated that the pre-processed data sets registered reliable. Only 2 of the 300 trials did not register correctly. The not pre-processed datasets registered only in 130 of 300 trials correctly. The computation time for one trial, using the complete extracted surface, was about 24 seconds on a machine with Intel(R) Xeon(TM) 3.06 GHz CPU running Linux. To decrease the computation time we tested the registration of the pre-processed data again with reduced numbers of surface points. By a reduction with factor two, six of the trials did not register correctly, with factor four, three, with factor eight, seven, and with factor sixteen 24 of each 300 trials did not register correct. The computation times were then approximately 12, 6, 3 and 1.5 seconds as the computation time is proportional to the number of surface points.

DISCUSSION

We demonstrated that it is feasible to register bone structures based on 3D ultrasound and MRI data. The registration was reliable for starting deviations which are realistic in an intraoperative setting. Reducing the numbers of surface points that were used for the registration diminished the computation time. But reducing them too much diminishes also the reliability of the registration.
We also showed that the pre-processing of the ultrasound data was important for the registration results. Still the use of pre-processing and the parameter of the pre-processing must be evaluated by a larger number of data sets.

A further field of work will be the automation of the bone surface point extraction because. To introduce a method into the clinical context, it is important to reduce the surgeon's preoperative work steps to a minimum.
Altogether our methods will allow minimally invasive routine surgeries for orthopedic diseases without expensive, inaccurate and time-consuming strategies.

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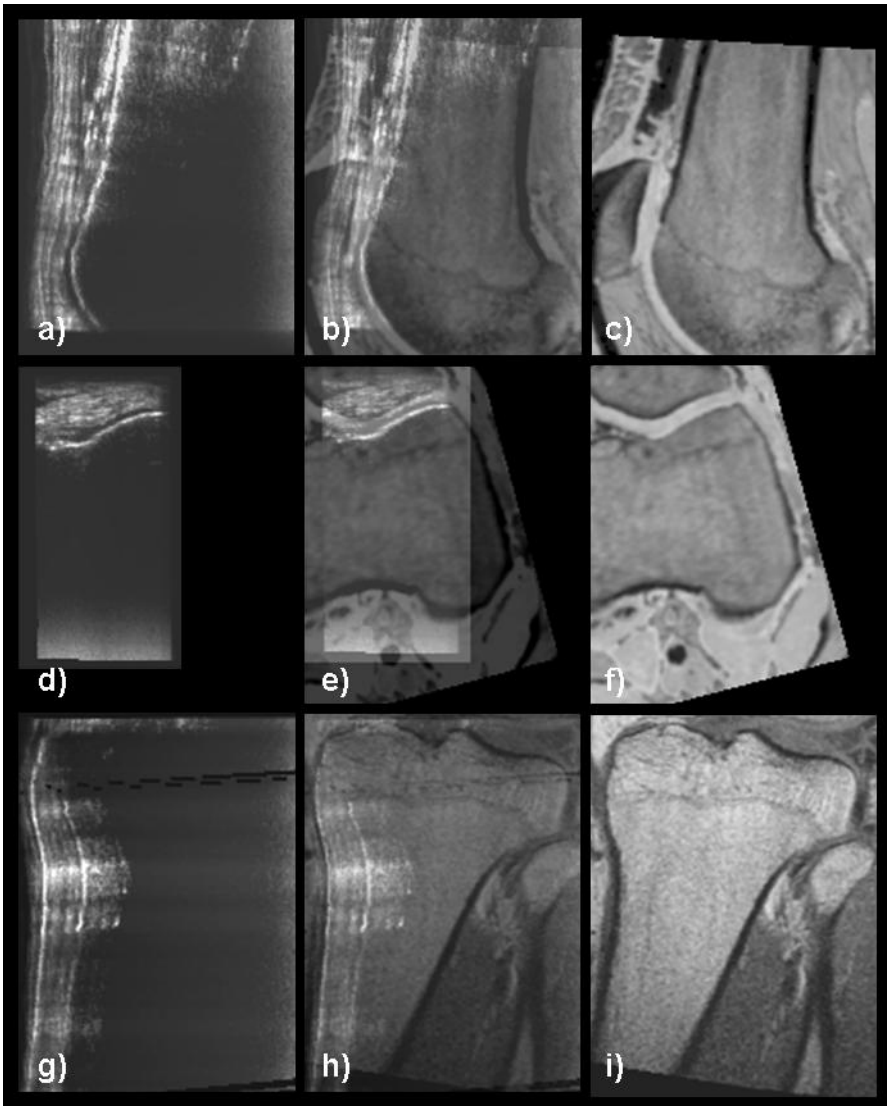

Caption – Figure 1
(a-c): Sagittal slices of the femur; (d-f): Axial slices of the femur; (g-i): Sagittal slices of the tibia. The images on the left show reconstructed ultrasound slices; the images on the right show the corresponding MR images; in the middle an overlay of both imaging modalities demonstrates the registration result.